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GENERAL DYNAMICS | ASTRONAUTICS

LIQUID RESPONSE TO AN

ORIENTATION MANEUVER

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This report describes an investigation of the
effect of the Centaur orientation maneuver on the
liquid fuel. A justification for model testing is
presented with scaling equations and the results of
preliminary tests. The main tests used a 1/90th
scale tank model and a trajectory determined from
the scaling equations. The behavior of the model
contents is described and mathematically analyzed.
The simulated fuel was appreciably (but not violently)
disturbed. We conclude that the LH_2 will not be
seriously disturbed by the 180° maximum turn although
there remains some possibility that a more gentle
maneuver might produce a more drastic effect. A
center vent should be usable soon after the orienta-
tion, perhaps in 300 seconds.   *author*

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LIQUID RESPONSE TO AN ORIENTATION MANEUVER

1.0 INTRODUCTION:

The ullage configuration in the Centaur fuel tank during zero-g was determined in 1961 for conditions of no mechanical disturbances. Later studies investigated the effect of heat input and mechanical devices (e.g. a center-vent tube and tank baffles) on this basic undisturbed configuration.

The plans for the Centaur call for (or did call for) this space vehicle to re-start twice in space. The tanks are to be 30% full during the coast period preceding the first restart and 10% full during the second coast. At the beginning of a coast, or zero-g, period the Centaur will be rotated so that the engines point at the sun to reduce the heat absorbed by the propellant tanks. It will then be maintained in this attitude by small rockets until it is re-orientated for another start. These major movements will certainly disturb the tank contents. This report documents a series of tests intended to determine the effect of the Centaur orientation maneuvers on the fuel-tank ullage configuration.

2.0 BACKGROUND:

2.1 The Centaur Orientation Maneuver:

During the orientation maneuver the Centaur is otherwise in zero-g, and the turn -- even though it is gentle -- may influence the propellants left in the tanks. First the vehicle is rolled about its axis so that the desired attitude can be reached by rotation in one additional plane. Then a combination of the 50-pound "ullage" rockets and the 4-pound attitude rockets are fired to produce an angular acceleration lasting about 25 seconds. The rockets are not fired continuously, but in a series of pulses equivalent

2.1 The Centaur Orientation Maneuver: (Continued)

to an average of about 0.048 degree/sec.[2] This angular accel-
eration is accompanied by a linear acceleration averaging about
0.028 ft/sec[2] for 10% fuel residuals or .018 ft/sec[2] for 30%
residuals (cf. Ref. E). The acceleration period is followed by
a period of constant rotation rate, the length of which is de-
termined by the required orientation angle. Then there is a
deceleration period which is the reverse of the acceleration.
The constant angular velocity being about one degree/sec., a
maximum (180°) turn takes about 180 seconds. The angular ve-
locity cancels to a zero residual at the end of the turn, but
the linear velocity does not. The re-orientation maneuver
follows a similar sequence.

The 180° turn was selected for the model tests because it
was expected to produce the greatest liquid disturbance and be-
cause it provided a residual velocity low enough so that the
model could be observed for a reasonable period after the turn
was completed.

2.2 Justification for Model Tests:

Obviously no full scale tests could be performed short of
a flight test; so models were used. Scale model tests are standard
in ship and aircraft development work and the dimensional analysis
approach has been highly developed for comparing model and full
scale effects in these fields.

In the new field of zero gravity, the parameters affecting
the oscillatory response of a liquid in a container are reduced
to the density, ρ, the surface tension, σ, the viscosity, μ, and
a characteristic dimension, D (see Ref. A). Since we see several
complete oscillations whenever a normal zero-g ullage shape is
disturbed, we know that the damping is relatively low. With such
low damping, the natural period of oscillation is essentially in-
dependent of viscosity. We know, moreover, that the orientation
maneuver is completed in a fraction of a zero-g ullage oscillation
period (about 650 sec). (See Section 3.0 for a discussion of the
higher frequency components.) Therefore we restrict ourselves to
ρ, σ and D, and write the following equation to represent the re-
lation of model time, T_m, to Centaur time, T_c.

$$T_m = \left[\frac{(\rho/\sigma)_m}{(\rho/\sigma)_c}\right]^{1/2} \left[\frac{D_m}{D_c}\right]^{3/2} T_c$$

The above equation is an algebraic re-arrangement of Weber's
number. Further such re-arrangement can be made to bring out an
acceleration term $\frac{L}{T^2}$ explicity. This manipulation is

2.2   Justification for Model Tests: (Continued)

equivalent to dividing Weber's number by Froude's
number and yields the following result which we used
to scale model to full size effects during the accel-
erated part of the turn.

$$a_m = \frac{(\rho/\sigma)_c}{(\rho/\sigma)_m} \left[\frac{D_c}{D_m} \right]^2 a_c$$

3.0   PRELIMINARY INVESTIGATION:

3.1   Reasons for the Preliminary Investigations:

The "preliminary investigations" were simple
rotations of scale models. Variously sized models
were photographed at scaled speeds to help visualize
the liquid action. These tests were conducted because
they would be done sooner than the much more difficult
"full-trajectory" test and because they could provide
a background for the later test. The effect of damping
on the high frequency components of the oscillations
was not known at that time, except that the damping
effects grow as the size is reduced. These tests,
therefore, were intended to show whether the higher
harmonics behaved the same in the different scales,
and thus to indicate whether we were justified in
using the small scale tests to predict full scale
liquid behavior.

3.2   Liquid/Liquid Rotations:

3.2.1   Selection of Scale:

Three models were chosen to provide a wide
spread in size: a 1/140th, a 1/35th, and a 1/10th.
The Weber number scaling introduced in Paragraph 2.2
was used to roughly determine the turn time. No
correction could be made for the difference between
the gas/liquid (Centaur) and the liquid/liquid (model)
case. However, the turn times were scaled (relative
to one another) by the Weber relation.

Liquid/liquid models (see Ref. B) simulated
zero-g with two immiscible, equal-density liquids in

3.2.1   Selection of Scale: (Continued)

a scaled fuel tank. There was reason (see Ref. A) to
believe that these models, originally intend to de-
monstrate static conditions, could yield useful dynamic
information. Models of 1/10th, 1/35th, and 1/140th
scale were chosen for convenience and were rotated at
rates of 26, 180, and 1500 degrees/sec respectively.
High speed movies were taken at 24, 128, and 1500
frames/sec so that the turns could be compared on
roughly the same time scale.

3.2.2   Equipment and Procedure:

The 1/10th scale model was rotated at a constant
speed by a geared-down electric motor. Rotation was
started by applying power to the motor. Rotation was
stopped by cutting power and allowing the model to
strike a stopping block.

The 1/35th scale model was rotated by a weight
attached to the model by a cable and pulley arrange-
ment, so that dropping the weight would start the
model rotating at the proper angular velocity. The
model was stopped by an arm and latch arrangement set
180° from the starting point.

The 1/140th scale model was mounted on a small
circular disc and ball bearing shaft arrangement.
The disc was turned back against a spring and latched
in this position. A solenoid was used to release the
latch at the proper time. The spring was in contact
with the disc for approximately 7° of rotation, the
model then rotated freely. To stop the model a wedge
shaped metal block slid between two leaf springs and
the model would cease to rotate in approximately 7°.

3.2.3   Results:

The photographs of the three rotations were
viewed in scaled time, (i.e., the apparent time for
each turn was about the same). The photos were re-
markably similar. "High" order vibrations of the
interface occurred at the same place in the turn and
lasted relatively the same time. Figure 1 shows still
photos of the two smaller models taken at the end of

3.2.3   <u>Results</u>:   (Continued)

the turn (just as the model began deceleration).
Both were turning in a clockwise direction. The
simulated fuel has held back --- note its concentra-
tion in the lower right corner. Compare also the
disturbances on the lower left side and the upper
right side. (The 1/10th scale model was about the
same). After the models were decelerated, the simu-
lated fuel continued to move in the direction of
rotation. There were only minor interface disturb-
ances and little or no "fuel" was torn loose from the
tank walls.

3.3   <u>Liquid/Gas Rotation</u>:

3.3.1   <u>Selection of Scale</u>:

Because the dynamic tests of the liquid/liquid
models did not really scale the liquid properties,
similar tests were made with a 1/140th scale liquid/
gas model. The turn time was scaled according to the
first equation in Section 2.2. In this case zero-g
was obtained during one-second drops. The 1/35th
scale model was not tested because its rotation time
was almost as long as the drop and it was too large
to fit in the drop capsule.

3.3.2   <u>Equipment and Procedure</u>:

The major components used for the drop rotations
were the one-second drop tower described in Ref. C
and a stream-lined, 200-pound drop capsule, 72 inches
long by 14 inches diameter. The capsule contained the
1/140th scale model and rotating device described in
Section 3.2.2.

The model was filled to 10%, 5%, or 45% with
Freon TF. The model adjusted to a rotation rate of
1800°/sec was turned 180°, 90°, or 20°. Both ini-
tially vertical and horizontal orientations were used.
The model was rotated about an axis passing through
its center; later the model was rotated in the same
plane but with the rotational axis tangent to the bulk-
head.

Motion pictures were taken at 400 fps with a
Millikan DBM-5 camera. Since the rotational plane of
the model was vertical, the pictures were taken with

3.3.2   Equipment and Procedure: (Continued)

the use of a mirror.

Timers, operated automatically from a start
switch, were programmed before the drops to operate
the drop mechanism, camera, and lights, and they also
started the model rotation during the drop. The time
delays used to start the model rotating after drop were
varied from zero to 0.5 seconds in 0.1 second incre-
ments.

3.3.3   Results:

All permutations of fuel fill, turn angle, delay
times, etc. produced generally the same results: the
liquid was swirled around the tank in the direction of
rotation leaving the ullage in the center. During
rotation the ullage became elongated and distorted with
considerable wave action, but the fuel was not broken-
up. Following the rotation the ullage remained in the
middle and the fuel motion, while continuing, began to
damp out. At the end of the turn the fuel moved along
the walls at about 3 in/sec and the waves had a velocity
of roughly 15 in/sec.

4.0   METHOD OF APPROACH TO THE TRAJECTORY TEST:

4.1   Early Airplane Tests:

It was first proposed to conduct this test in a
C131 airplane during zero-g trajectories. Two pre-
liminary flights with a rather crude but adequate
capsule were made to determine the effect of dis-
turbances in the airplane flight path. Model size
and turn time are inevitably linked as shown by the
first equation in Section 2.2 --- the larger the
model, the longer the time required. A practical
model for airplane tests was so small that it came
within the range of drop tower tests. In addition,
an initially flat ullage could not be obtained in
the aircraft test. It was therefore decided to do
the testing in the drop tower.

4.2   Selection of Scale:

4.2.1   The model to be used was desired to be as large as
possible, the size being limited by two things -- the
free-fall time available and the drop capsule size.
Increasing either the drop time or the capsule size
could increase the drag to an intolerable point. More
than just the time for the rotation itself was required,
since time to develop a hemispherical ullage was desired
before the turn, and coast time would be needed after the
turn to determine the state of the tank contents and the
degree of damping. The compromise selected was the
1/90th scale model, the trajectory of which could just
be fitted into a 20-inch diameter capsule and the
characteristic times of which were below two seconds.

4.2.2   Once the size and liquid (Freon TF) were selected
the other parameters could be determined from the values
in Paragraph 2.1 by the principles outlined in Paragraph
2.2. Table I lists these parameters.

              Since the model was turning on its axis while moving
along the trajectory, it was necessary to use time in-
crements to perform the calculation. The time increments
used were:

Acceleration (less than 0.172° turn)	1/100 of acceleration period
Acceleration (0.172° to 15° turn)	1/18 of acceleration period
Coast	1/10 of coast period
Deceleration (15° to 0.172° from end of tra-jectory)	1/18 of acceleration period
Deceleration (less than 0.172° from end of tra-jectory)	1/100 of acceleration period.

For each time increment, the average values of the
acceleration and the angle of turn were used to cal-
culate the incremental velocity and distance. A
summation of the velocities and distances at the end

4.2.2 (Continued)

of each time increment provided the trajectory. See
Figure 2 for the 1/90th scale model trajectory for a
10% fuel load.

4.3   "Propulsion" of the Model:

There were two alternatives for the actual "pro-
pulsion" of the model. We could either use an arrange-
ment where the model would be rigorously guided through
its proper path relative to the freely falling capsule
by cams, levers, gears, etc, or we could use an arrange-
ment where the model was free to move in a plane under
the influence of properly calibrated "impulses". The
latter approach was used, with air nozzles supplying
the impulses (timed blasts from the nozzles were
directed at vanes mounted on the model). The con-
straint of the model to a plane allowed the system to
be set up and adjusted on the ground. Gravity had no
effect on the trajectory during these adjustments be-
cause the capsule was turned on its side and carefully
levelled to bring the constraint plane horizontal.

5.0   TEST EQUIPMENT:

The major components of test equipment used for
the Centaur-orientation drop test were as follows:
the 2-second drop tower, sand box, drop tower winch,
drop release, drop capsule, drop-capsule trailing
cable, camera, and timing system. The drop tower,
winch and sand box were existing facilities, although
considerable effort was expended in developing tech-
niques to reduce the impact on the drop capsule. The
capsule test equipment is discussed below under the
headings of Mechanical Details and Electrical Details.

5.1   Mechanical Details:

The model selected was a 90th scale lucite tank
equipped with two bearing attachments about midway
on the tank and on opposite sides. (see Figure 3).
The bearing attachments also served as fastening
points for two air vanes, one on each side. The
vanes were approximately 1 x 1 inch in size and

5.1   <u>Mechanical Details</u>:   (Continued)

could be turned and offset relative to the axis through
the model bearings. After adjustment they were locked
to the model. The model was free to move but restricted
to a plane. This was arranged by suspending the model -
by its bearings - in a light, rigid two-arm linkage
attached to the drop capsule. The arm closest to the
model was made as a truss assembled by glueing together
sticks carved out of wooden tongue depressors. The
other arm was a block of styrofoam covered with glass
cloth and epoxy. All bearings were miniature ball
bearings and the linkage had very low friction. The
weight of the two arms was a small fraction of the
weight of the model (about 1/10) so that the inertia of
the model was the dominant factor in the motion of the
arm-model system. The 10% and 30% fill conditions re-
quired different trajectory lengths, about 14 and 9
inches respectively, and the linkage design and gas
nozzle position allowed for either case.

It was of course necessary to take precautions
to secure the model-linkage system before the capsule
hit the sand. A nylon sling was attached to the model
and secured lightly (with sticky tape) to suitable
points of the linkage. The other end of the sling was
wound around a drum driven by a small air motor. Shortly
before impact a solenoid valve controlled by the timing
system would activate the drum, and the model would be
pulled up against a foam pad in the top of the trajectory
area (where it normally would be floating about after
the end of the turn). This worked satisfactorily and
the sling did not otherwise disturb the trajectory.

The model was held in its start position by a per-
manent magnet pulling very lightly on 4 steel screws
that held the detachable bottom of the model to the rest
of the model. All gas needed for the trajectory blasts
and for the air motor was stored in a small nitrogen
bottle that was permanently installed in the capsule and
refilled after each drop.

A mirror arrangement gave movie coverage of selected
parts of the total trajectory by proper choice of mirror
locations.

5.2   Electrical Details:

        The electrical system can be classified into two
categories: the components controlling the trajectory
and those connected with auxiliary functions. The
former group consists of the electro-mechanical timers,
electronic preset counters, pulse oscillator, and
variable-width power-pulse generators used to control
the gas blasts. The auxiliary operations are: the
gravity-actuated circuit, the camera and light circuit,
the wind-up system and the various manual by-pass
switches for all timing sequences. The electrical and
timing systems, Figures 4 and 5 operated the whole ex-
periment from a single start switch. Each of the timing
functions were individually adjusted and preset.

        One of the components of the timing system that may
require clarification is the gravity-actuated lock cir-
cuit. The closure of the zero-g switch triggers the lock
circuit which allows the automatic sequencing of the re-
maining timers to begin. Its purpose was to (1) provide
a time reference for the remaining timing functions and
(2) insure against damage of the experiment in case of
drop mechanism malfunction.

        The other system that was specially built for this
experiment was the variable-width power-pulse generators,
Figure 6. These turned the two trajectory valves on and
off to provide the proper impulse to the model.

6.0   TEST PROCEDURE:

6.1   Pre-Drop Procedure:

        The model was filled to 30% of its volume. The
liquid used for this experiment was Freon TF (Freon 113).
Water was used initially on two drops for general informa-
tion and comparison.

        A careful adjustment sequence was required before
each drop series. The capsule assembly was first leveled
to achieve a vertical orientation of the rotational axis
of the primary suspension arm. The primary and secondary
arms were then paralleled by screw adjustments. When the
leveling adjustment was complete gravity did not move the
model in any orientation of the arms.

        Vane adjustment was done with all timers and pressures

6.1   <u>Pre-Drop Procedure</u>:   (Continued)

set to the approximate values expected during drop
operations. Then adjustment of both the off-set and
the inclination was made on the two vanes.

The inclination adjustment on the acceleration
vane determined the direction of the model's initial
trajectory. The inclination adjustment on the de-
celeration vane partially determined the model's second
coast direction and velocity. The effects of these
settings varied with gas pressure and pulse width.

The offset adjustment on the first vane was made
so that the model had rotated the proper amount at
the end of the first coast period. A similar adjust-
ment on the second vane, together with an adjustment
of the decelerating pulse width, was made so that the
model had the desired rotational position during the
second coast period.

Taken all together, the adjustment process was
quite puzzling and critical. Each adjustment had to
be compensated by a re-adjustment of something else.

6.2   Drop Procedure:

The following table gives typical timer settings used during the drop tests:

EVENT	TIME BETWEEN EVENTS (Sec)
Camera and lights on	
	1.5
Release initiated	
	0.01
Zero-g switch closes	
	0.020 to 0.300
Acceleration gas blast on	
	0.040
Acceleration gas blast off	
	0.240 — 0.320 — 1.00 — 3.0
Deceleration gas blast on	
	0.040
Deceleration gas blast off	
Winder on	
All power off	

Three different portions of the total trajectory were photographed separately by changing mirror position, mirrors, and/or camera lenses. These portions were: (1) the start position; (2) a middle or coast position; and (3) the deceleration and subsequent second coast period. The camera used was a Millikan DBM-5. The film speed was 400 frames/second. The two film types used were ER Tungsten and Tri-X negative.

6.3   Drop Capsule Catching Method:

Figure 7 shows the conditioning of the sand in
the drop capsule catch box. A method of wet sand
catching was used rather than the more common dry
sand catch because of the difficulty in keeping the
sand dry enough to prevent packing during seasonal
rain over the test interval. The packing of the
moist sand decreased the capsule penetration depth
and increased the acceleration forces to more than
the maximum allowable for the installed photographic
equipment. Tests indicated that a small amount of
water content promoted the worst packing and that in-
creased water content decreased this condition.

The use of water alone was unsatisfactory as it
loosened or floated the sand excessively and allowed
the capsule spike to strike bottom. A concrete vi-
brator was procured to firm the loosened sand. The
method of inserting the vibrator into the hole left
by the nose spike, and washing the sand down around
it while withdrawing the vibrator slowly provided
satisfactory an. repeatable results.

The acceleration forces were reduced from
approximately 40 - 45 G with dry sand to 20 - 30 G
with wet sand. Slightly damp sand produced accelera-
tions in excess of 70 G. The photographic equipment
was limited to 50 G.

This wet sand catching method reduced the maximum
acceleration forces and permitted drop testing to con-
tinue outdoors during the period of seasonal rains.

7.0   RESULTS AND DISCUSSION:

7.1   Introduction:

The following verbal discription of the capsule
orientation maneuver is supplemented by a short movie
of the drop tests. This movie is available from Dept.
577-6.

7.2   Start of Trajectory:

Time delays of 20, 100, and 300 msec after capsule
drop were used before the start of the trajectory

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7.2   Start of Trajectory: (Continued)

sequence. The liquid was initially at the bulkhead end
of the model in one-g. During the 20-msec zero-g time
delay the ullage had just started to form. After 300
msec, the longest time delay used, the ullage was essen-
tially completely formed into a hemispherical configuration
before starting the maneuver.

At the onset of acceleration the liquid started to
fall back from its concave shape. It reached a roughly
flat surface and its kinetic energy caused a dome to form
in the center near the end of the acceleration period. In
the long-delay-time tests enough kinetic energy was left
in the dome to form an appreciable jet squirting forward
in the center of the tank.

The natural period of small oscillations of liquid
in a cylindrical basin of uniform depth is given by the
following relations.[*]

$$P = 2 \pi N \sqrt{\frac{D/g}{\text{Tanh } (h/N^2 D)}}$$

Which, for a deep tank ($h > 2N^2 D$), reduces to:

$$P_D \approx 2 \pi N \sqrt{D/g}$$

Or, for a shallow tank ($h < .3 N^2 D$):

$$P_S \approx 2 \pi N^2 D \Big/ \sqrt{gh}$$

Where, in consistent units,

P   is the period of oscillation

D   is the tank diameter

h   is the depth of the liquid

g   is the gravity (or acceleration) field

N   is a dimensionless number derived from
integration of the differential equations
of motion. Values of N ($= 1/\sqrt{2ka}$ of Ref. D)
are tabulated below for six of the simplest
modes of oscillation.

(Continued)

(*) Ref D, pp 283, 287, 440 and 441

7.2 Start of Trajectory: (Continued)

MODE	SYMMETRICAL	NON-SYMMETRICAL
1	.361	.621
2	.298	.306
3	.222	.242

In the laboratory we timed water oscillations in basins shaped like and unlike the bottom of the Centaur LH$_2$ tank in order to verify the applicability of the above equations to the problem in hand. It appeared that the simplest symmetrical slosh in the 30% full 1/90-scale model would have, during the 94.5 ft/sec acceleration, a period of about .08 seconds. The calculated P and P$_D$ differ by less than 1%, and, although no tests were made at this small scale, the larger scale basin tests checked the theory within 5 to 10%.

The period for large amplitude oscillations is probably appreciably longer (as with a pendulum) than the above relations indicate. Accepting this, the central squirt can be explained on the basis that the .04 seconds acceleration period is somewhat shorter than one half of the .08 + seconds natural period of the liquid.

7.3 Mid Position of Trajectory:

At the end of the first acceleration, most of the liquid was still at the bulkhead end. A rounded ullage then started to form and was completed before the deceleration started. The ullage was greatly displaced by the rotation of the tank. The liquid displacement was opposite to the rotation, with much of the liquid lying along one side of the tank just before the deceleration.

7.4 Deceleration and Coast:

During this period the fuel rotated as a whole up and down the walls and across the ends of the tank. This sloshing occurred because the liquid continued to rotate for a time after the tank rotation stopped and

7.4   Deceleration and Coast: (Continued)

because the linear deceleration of the tank caused a
higher head pressure along the one wall (because of a
higher column of liquid) than along the opposite one.

The liquid moved in the direction in which the tank
had been rotating. After crossing the bottom, it trav-
elled up the side of the tank wall in a column. It
appeared to be somewhat like a wave in that it had a
generally blunt front. It displayed some feathering
along the front edge nearest the center of the tank.
The velocity of this column was measured from motion
pictures to be approximately 20 in/sec. Meanwhile the
level of. fuel above the bulkhead, as the liquid column
was moving up the side, decreased to a depth where the
top of the dome was just uncovered.

The 20 in/sec liquid velocity is appreciably greater
than the tangential velocity (say 5 in/sec) of the model
tank rotation. The extra kinetic energy apparently came
from the linear velocities and accelerations of the system.
This seems quite reasonable. The first non-symmetrical
oscillation mode period calculates to .13 sec. Allowing
for some slowing of this oscillation for the large am-
plitude swing, the .04 second deceleration is tuned to
just about a quarter cycle. This tuning is verified by
the observation that the liquid crossed the tank bottom
at just about the end of the deceleration period.

After the deceleration, during the second coast
period, this liquid motion continued. The fuel moved
up and around the front of the tank and then back down
toward the bulkhead. The column became less distinct
with time as it moved across the top of the cavity.

When it reached the side opposite the one it had
initially traversed, most of it flowed along the walls.
The first portion of this liquid flowed toward the bulk-
head with a velocity of about 40 in/sec. The first part
of this liquid reached the bulkhead area in about 0.13
seconds after the start of the deceleration. A small
remainder broke up into globules which impinged on the
intermediate bulkhead. This impingement caused some
bubble formation near the top of the dome.

(Continued)

7.4   Deceleration and Coast: (Continued)

        After the fuel started to move back to the bulkhead
the liquid completely covered all the walls. The fuel
was in a somewhat confused condition but with a discern-
able central ullage. Some damping became apparent during
th second coast.

7.5   Effect of Baffles:

        In some of the tests anti-vortexing baffles were
placed in the model. These baffles caused no noticeable
difference in the liquid behavior.

7.6   The Wrong Trajectory:

        As the reader may have noticed, the test apparatus
was adjusted for the long (10% fill) trajectory, and
the tests were run with the model tank 30% full of liquid
("fuel"). This was a mistake --- the fact is inescapable
--- which was not uncovered until after the test series
was completed. Reviewing the test results, we are, how-
ever, convinced that they would not be appreciably changed
by testing with the short trajectory. Such a test run
would, moreover, cost considerable time and money, so we
secured the apparat   nd prepared this report.

        The 30% fill was chosen for the orientation tests
because more trouble might be expected with liquid dis-
tribution when more liquid is aboard, and because more
Centaurs will coast with 30% fill than with 10%. The
long trajectory used in the testing differs from the
short (30%) trajectory in that the accelerations are
stronger, the velocities higher and the linear distances
longer. Timing and all angular characteristics are the
same for both trajectories. Taking the trajectory step
by step, we find that the short trajectory would change
the picture as follows.

        The initial acceleration, being gentler, would not
excite the center squirt so strongly. This lower accel-
eration, however, would stretch the natural period of
oscillation by about 25%, probably bringing the .040
seconds acceleration period nearer to the pessimum ¼
cycle tuning. With the factors offsetting each other
the squirt might be weaker or stronger, but not very
much. The end result will, however, be essentially

7.6 The Wrong Trajectory: (Continued)

unchanged, for the squirt will impinge on and coalesce with the liquid on the walls before the deceleration.

The deceleration will almost inevitably produce less slosh with the short trajectory than with the long one. Not only is the deceleration less severe, but also the difference in tuning, if enough to change the picture, can only improve it.

8.0 CONCLUSION:

From these results we conclude that the fuel in the Centaur during a 180° orientation maneuver will be appreciably (but not violently) disturbed. During the first acceleration period the liquid'surface will be relatively smooth. During the deceleration the surface will be considerably more agitated. After the maneuver, the ullage will still be in the center; the liquid will be on the walls; the interface will be disturbed but still essentially continuous. A center vent should be usable soon after the orientation, perhaps in 300 seconds.

There remains a possibility that vehicle accelerations differing in magnitude and duration from those we studied may end with the liquid velocities high enough to seriously disturb the arrangement of liquid and gas in the tanks.

R E F E R E N C E S

(A)   Hansen, J. L.; Zero-G Report: "Liquid Behavior
       Scaling"; Test Laboratories Report #55D 859-8;
       May 1962

(B)   Wood, G. B.; Zero-G Report: "Liquid/Liquid
       Models"; Test Laboratories Report #55D 859-9;
       June 1962

(C)   O'Hanlon, T. W.; Zero-G Report: "LH_2 Nucleate
       Boiling"; Test Laboratories Report #55D 859-1;
       February 1962

(D)   Lamb, Sir Horace; "Hydrodynamics"; Cambridge
       University Press, 1932

(E)   Merino, F.; Aerophysics (Dept. 595-1)
       Notebook # 143; pg 22.

(F)   Memo #577-6-635; Wood, G. B. to Sherley, J. E.;
       "Zero-G Reference Material".

TABLE I

SCALING PARAMETERS

PARAMETER	SCALE BASIS	FILL	CENTAUR PARAMETER	SCALE EQUATION	SCALE FACTOR	1/90 SCALE PARAMETER
Trajectory Time	Weber's Number	Any	180 sec	$\left[\dfrac{(\rho/\sigma)_m}{(\rho/\sigma)_c}\right]^{1/2}\left[\dfrac{D_m}{D_c}\right]^{3/2}$	0.0018	0.318 sec
Linear Acceleration	Froude's and Weber's Numbers	10%	0.028 ft/sec²	$\dfrac{(\rho/\sigma)_c}{(\rho/\sigma)_m}\left[\dfrac{(Dc)}{(Dm)}\right]^{2}$	3393	94.5 ft/sec²
		30%	0.018 ft/sec²		3393	60.3 ft/sec²
Angular Acceleration	Geometry	Any	0.048 deg/sec²	$\left[\dfrac{t_c}{t_m}\right]^{2}$	305,000	14,600 deg/sec²

WHERE:

σ = Surface tension of liquid

ρ = Density of liquid

D = Diameter of tank

t = Time

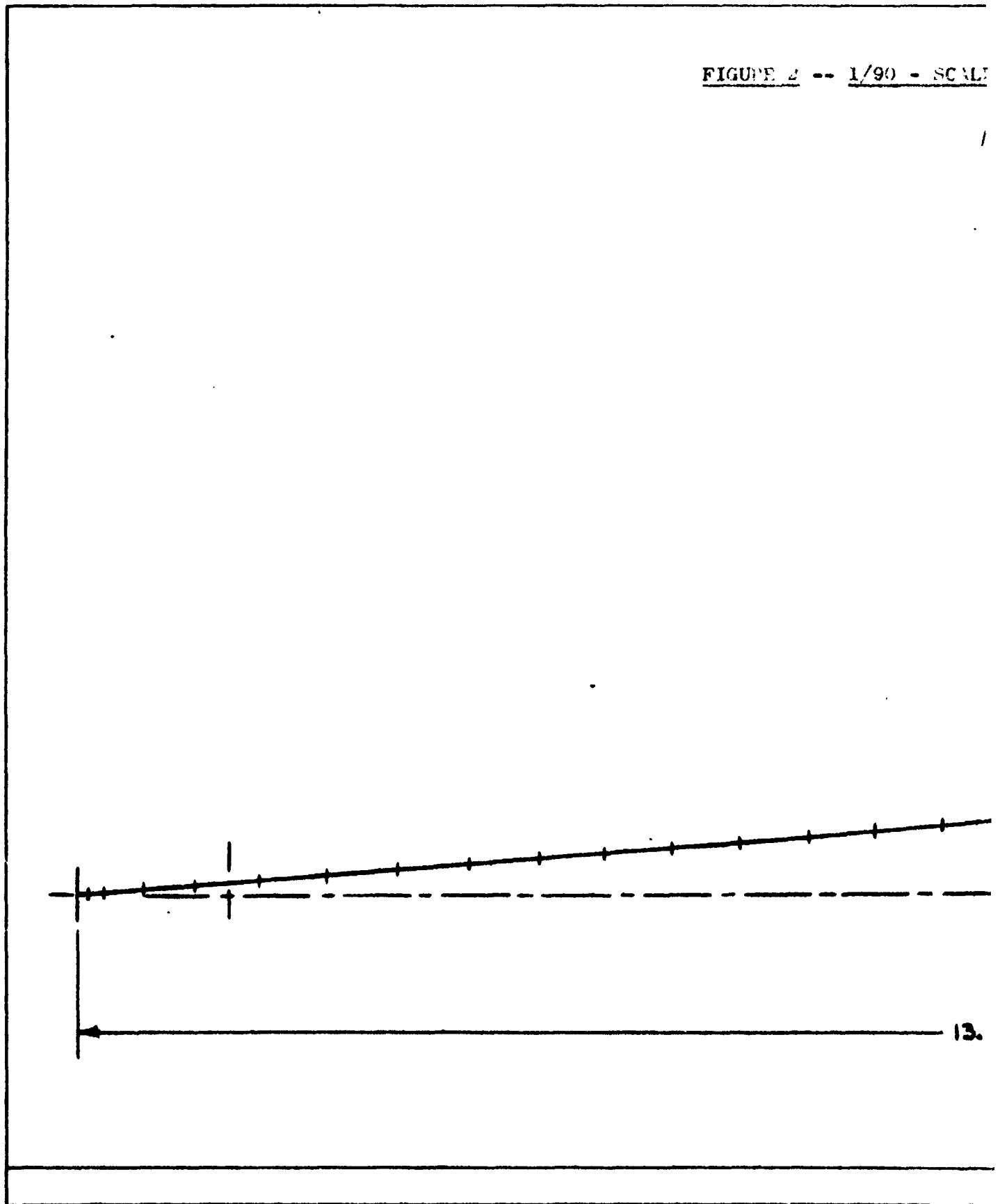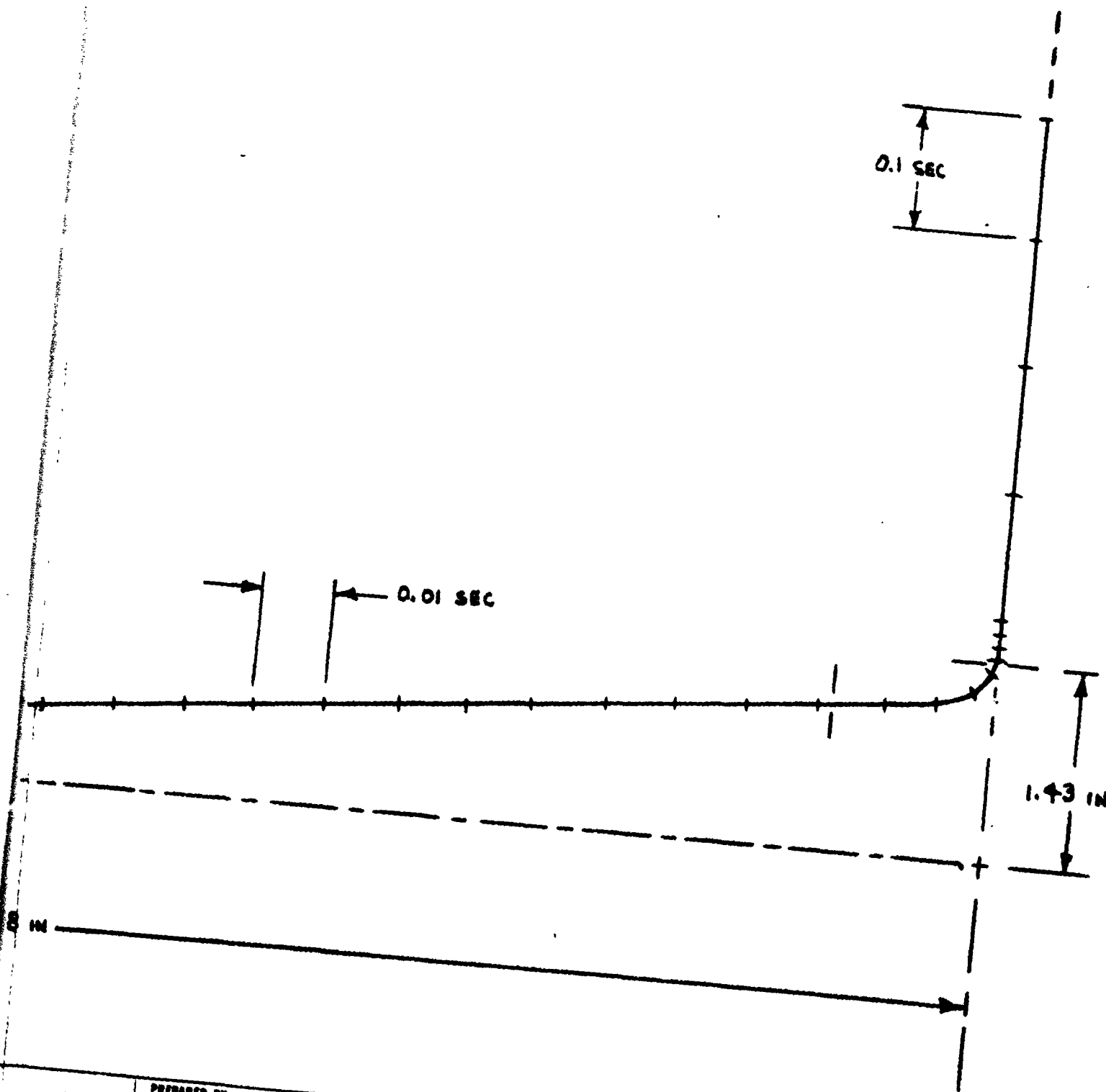Subscript c refers to the Centaur

Subscript m refers to the model

1/140th scale

1/35th scale
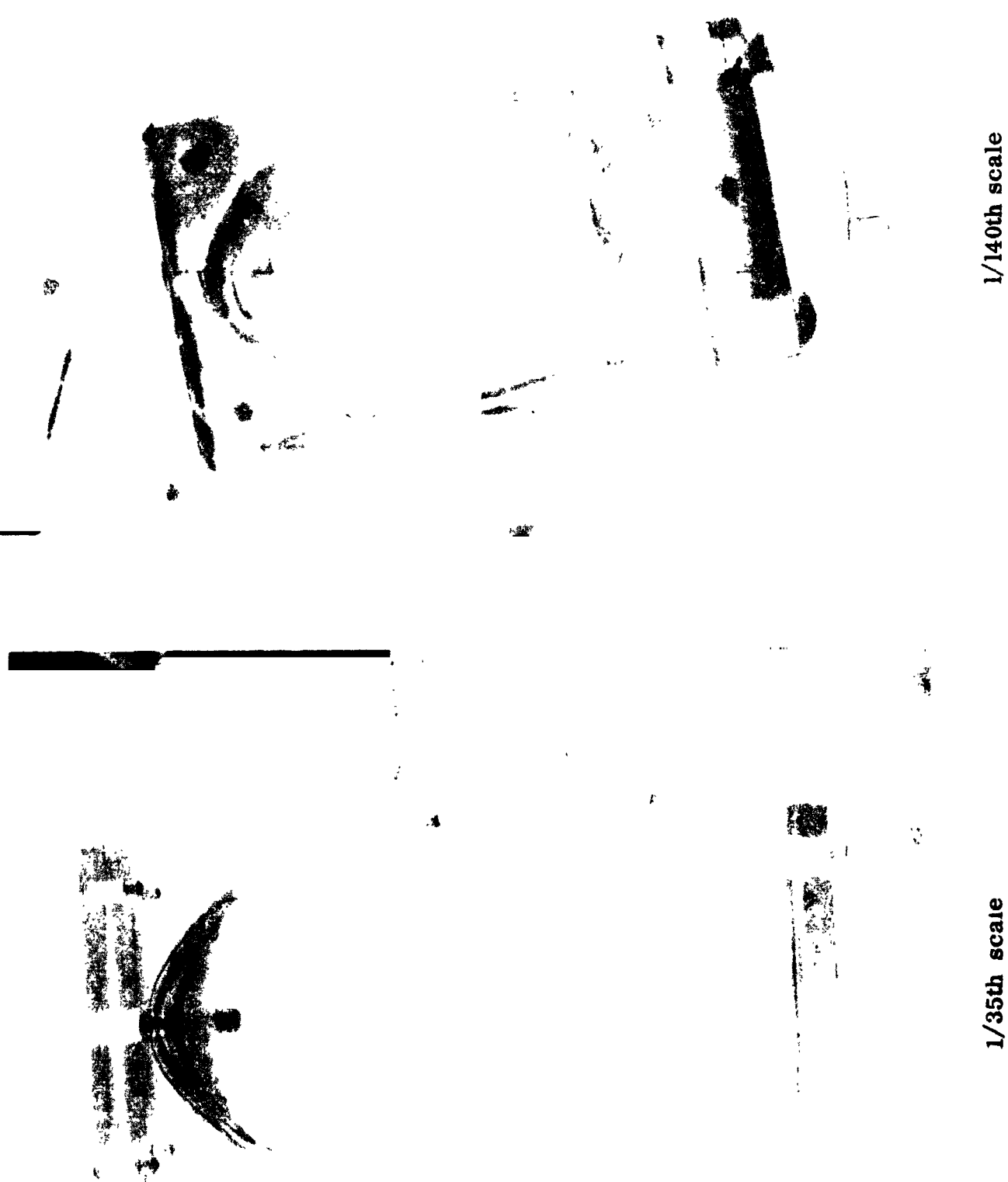
Fig. 1. Rotating liquid/liquid models

FIGURE 2 -- 1/90 - SCALE

13.

MODEL TRAJECTORY - 10% FILLING

0.1 SEC

0.01 SEC

1.43 IN

8 IN

PREPARED BY

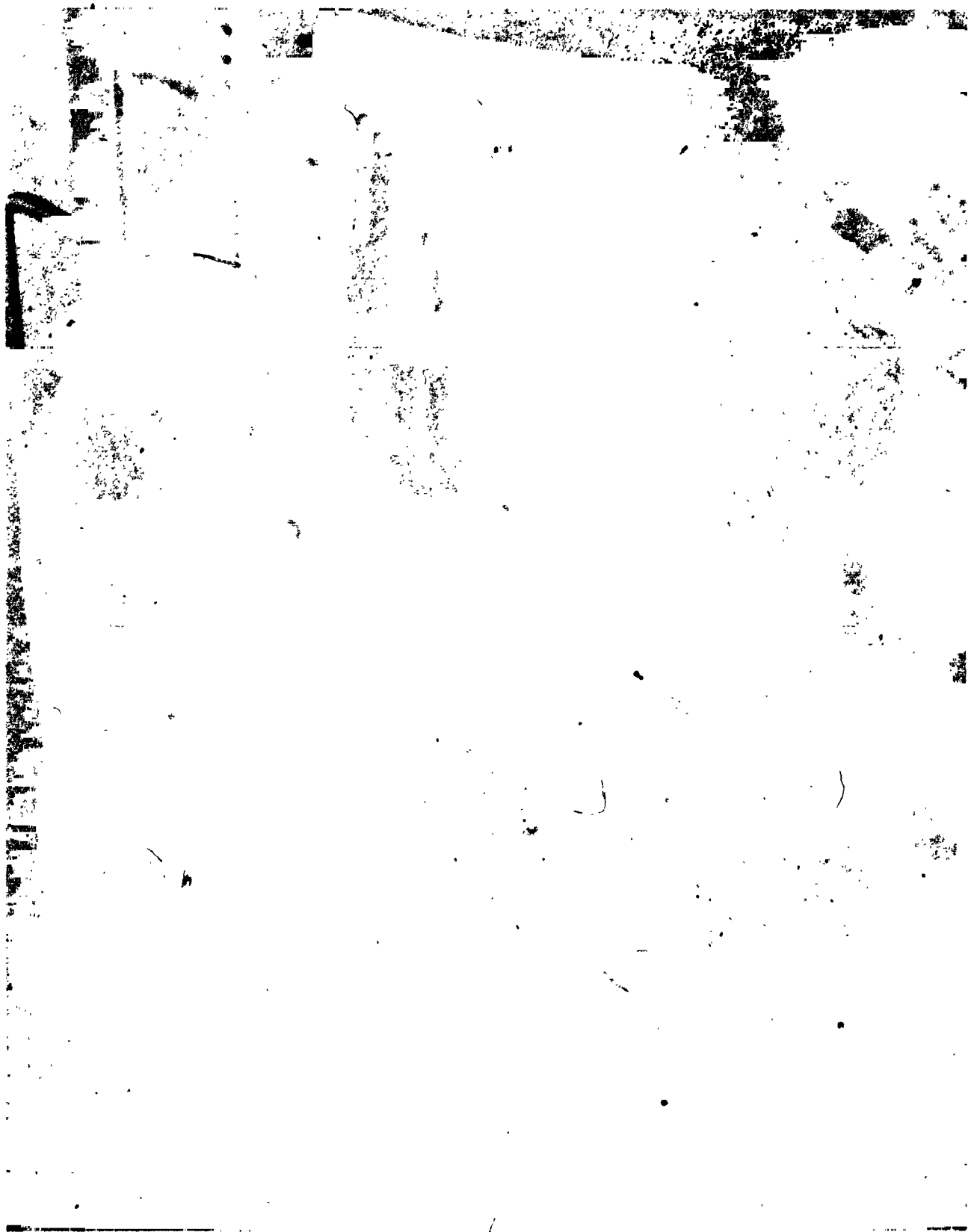DATE   CHECKED BY

DATE   REVISED BY

DATE

FIGURE 4
SIMPLIFIED BLOCK DIAGRAM
ELECTRICAL SYSTEM
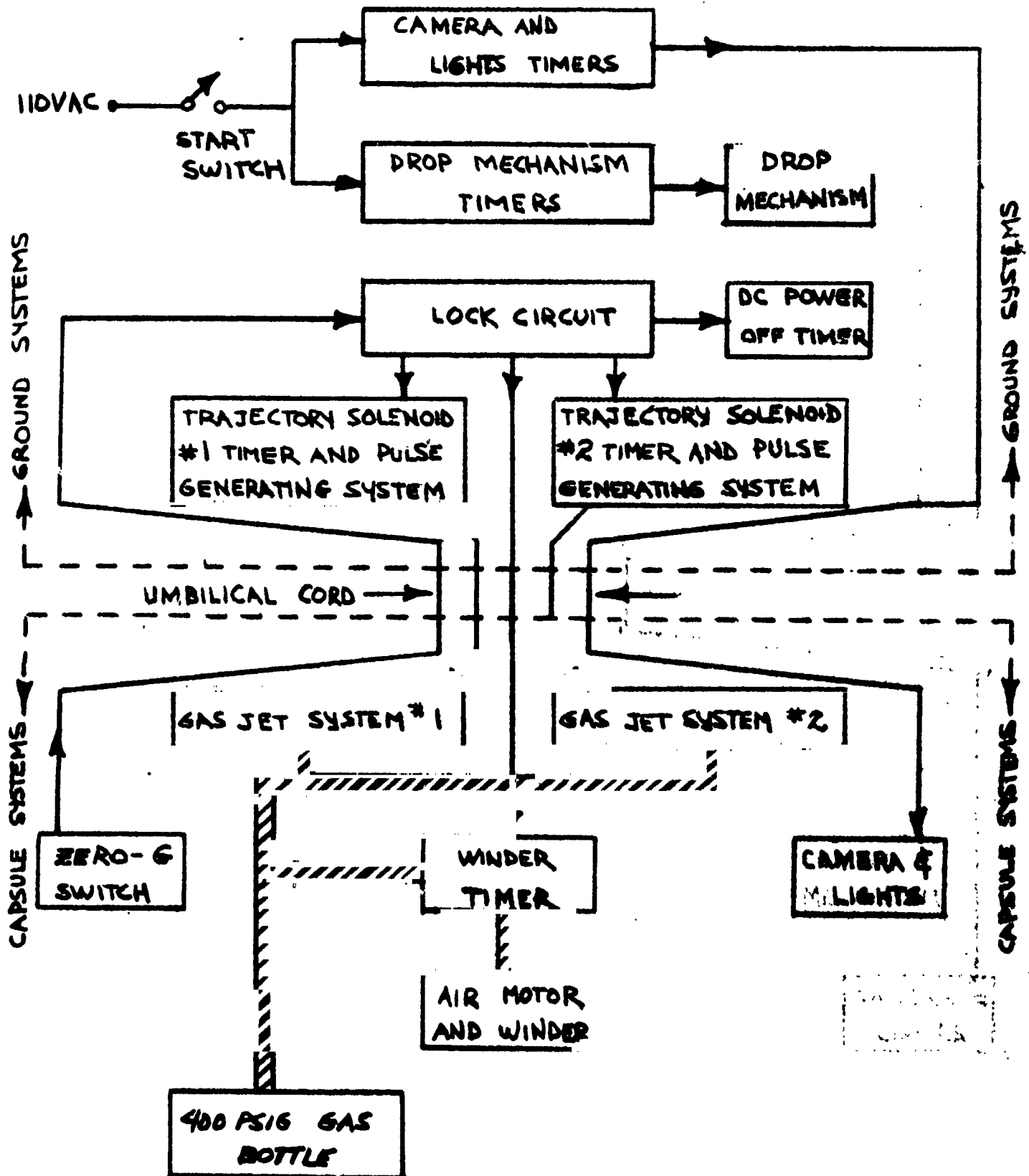
FIGURE 5

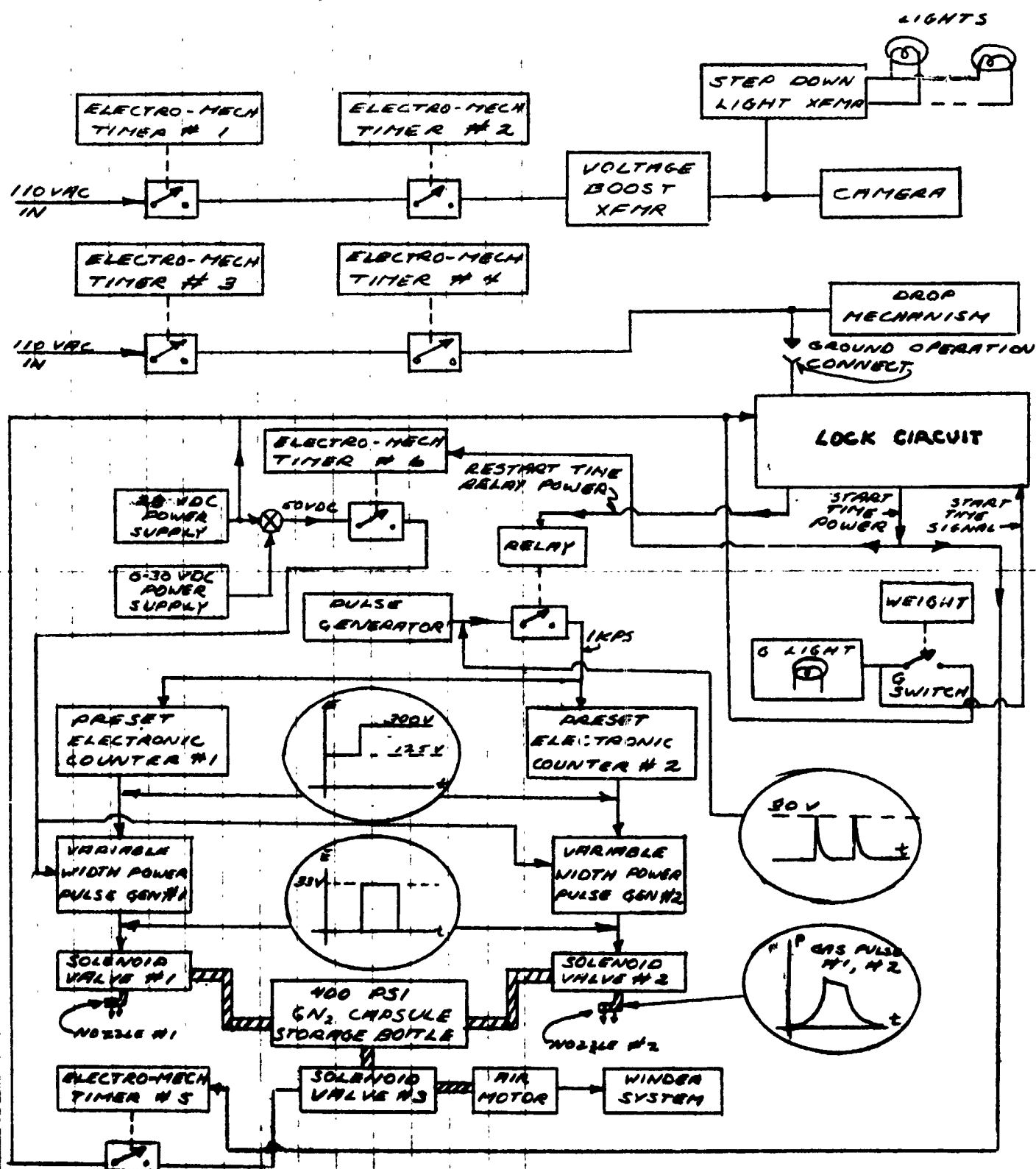## BLOCK DIAGRAM OF
TIMING AND ELECTRICAL SYSTEM

ALL TIMERS HAVE BYPASS SWITCHES — NOT SHOWN
ALL INPUT AND TIMED OUTPUT VOLTAGE CIRCUITS
HAVE INDICATOR MONITORING LIGHTS — NOT SHOWN

FIGURE 6

VARIABLE WIDTH POWER PULSE GENERATOR CIRCUIT